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Phase Shifting Diffraction Interferometry for Measuring Extreme Ultraviolet Optics

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Abstract: This paper describes a visible light diffraction interferometer for measuring reflective EUV optics that can intrinsically achieve a required absolute figure accuracy of 0.25nm rms.

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Introduction: Extreme ultraviolet projection lithography operating at a wavelength of 13nm is based on all reflective imaging systems made up of three to five multilayer coated mirrors. If these imaging systems are to achieve diffraction limited performance, the deviation of the wavefront from spherical in the exit pupil must satisfy the Maréchal condition of $\lambda/14$ rms where λ is the operating wavelength. The wavefront error must therefore be less than 1.0nm rms. If the imaging system is made up of four mirrors, the error contribution from each mirror can be no larger than 0.5nm rms (assuming uncorrelated errors), or 0.25nm rms surface figure error (due to the doubling of the error on reflection).

Fabrication of these mirrors requires real-time metrology to serve as the feedback mechanism for the polishing process. Visible light interferometry is the metrology of choice for optical fabrication for several reasons: the unit of measure is the wavelength of light which is stable and traceable and can be further subdivided to give increased resolution; the surface of the optic under test can be spatially sampled at many points ($>10^5$) simultaneously; and the data acquisition time is typically less than one second. For the characterization of most optics, where $\lambda/20$ to $\lambda/50$ rms accuracy is sufficient, commercial interferometers are adequate. However for EUV optics this is not the case. For a testing wavelength of 633nm, $\lambda/50$ corresponds to about 12.5nm, a factor of 50 larger than the accuracy required for EUV mirrors.

The accuracy of surface figure interferometers is limited by several factors, the two most important being the quality of the reference (whether an optical surface, null lens or computer generated hologram) and the quality of the auxiliary optics. Since interferometry is a comparative technique the accuracy of the reference directly affects the accuracy of the measurement of the optic under test. This is the primary source of error in an interferometer. Although several methods have been developed to increase the accuracy by making a series of measurements with the reference in transposed positions, the accuracy needed for EUV optics has not been demonstrated.

A secondary source of error involves the auxiliary optics outside the interferometer cavity that define the wavefront incident on the interferometer. This wavefront typically deviates from a plane or sphere by a significant fraction of a wavelength. The effect it has on a measurement is usually dismissed using "common path" arguments. To first order this is true, however an imperfect incident wavefront produces a local shear between the measurement and reference wavefronts. The resulting measurement error cannot be ignored when qualifying EUV optics.

In general, if one looks at the development of surface figure interferometry over the last twenty years or so, great strides have been made in data acquisition and phase measurement with the advent of CCD cameras and N-frame phase algorithms. Little, however, has been done to eliminate the fundamental errors caused by the interferometer itself. One approach is to make the reference and auxiliary optics better, but this has diminishing returns. Another approach is to characterize the errors in the interferometer very accurately and subtract them from the measurement of the optic under test. This can work well for a specific optic under test but is quite tedious and must be repeated for each new optic.

The approach described in this paper is different. It is based on simplifying interferometry - minimizing the number of critical components and eliminating those parts that reduce accuracy, including the reference and auxiliary optics.

Interferometer: The interferometer described here is based on diffraction[1]. Diffraction is a fundamental process that permits the generation of near-perfect spherical wavefronts over a specific numerical aperture by using a circular aperture with a radius comparable to the wavelength of light. Figure 1 shows the deviation of a diffracted wavefront from a true sphere. Over a finite numerical aperture this wavefront can be arbitrarily good. For example, if the aperture has a radius of 2λ then the deviation of the diffracted wavefront from spherical is less than $\lambda/10{,}000$ over a numerical aperture (NA) of 0.3 in the far field of the aperture. Using this principle, two independent wavefronts can be generated - one serves as the measurement wavefront and is incident on the optic or optical system under test and the other serves as the reference wavefront. Since they are generated independently their relative amplitude and phase can be controlled, providing contrast adjustment and phase shifting capability. This concept can be implemented in several different ways. The one described here is based on single mode optical fibers which provide the diffracted wavefronts.

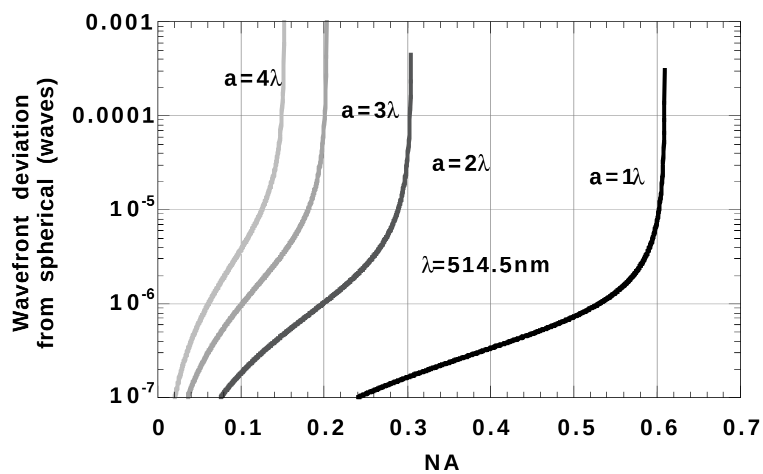


Figure 1. Plot of the deviation of a diffracted wavefront from spherical for different aperture radii **a**.

Figure 2 shows one of the basic principles of operation. Light leaving the end of the single mode optical fiber diffracts to a spherical wavefront over an extended angular range. Part of this wavefront is incident on the optic under test and is reflected back toward the fiber. This aberrated wavefront reflects from a semi-transparent metallic film on the face of the fiber and interferes with part of the original spherical wavefront to produce the interference pattern. Figure 3a shows the interferometer for testing optics where the end of the fiber is placed at a common conjugate. In this configuration two temporally incoherent beams are launched into the same fiber. One beam is first reflected from a retroreflector mounted to a piezoelectric phase shifter and the other beam is delayed by a path length equal to the round-trip distance between the fiber face and the optic under test. Interference on the CCD camera takes place between the phase shifted wavefront that is reflected from the optic under test and the delayed wavefront directly from the fiber.

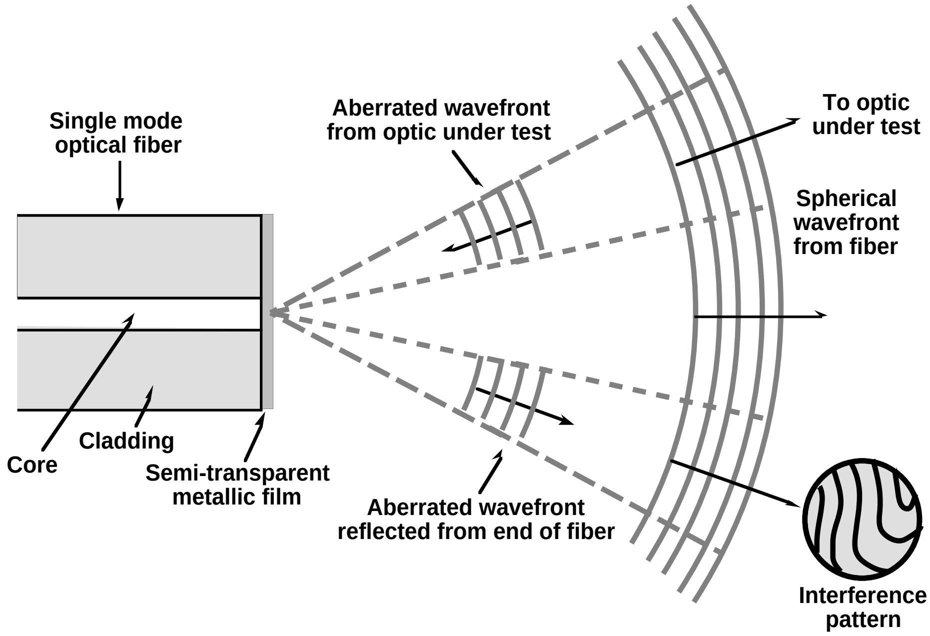


Figure 2. Principle of operation of the phase shifting diffraction interferometer using a single mode optical fiber.

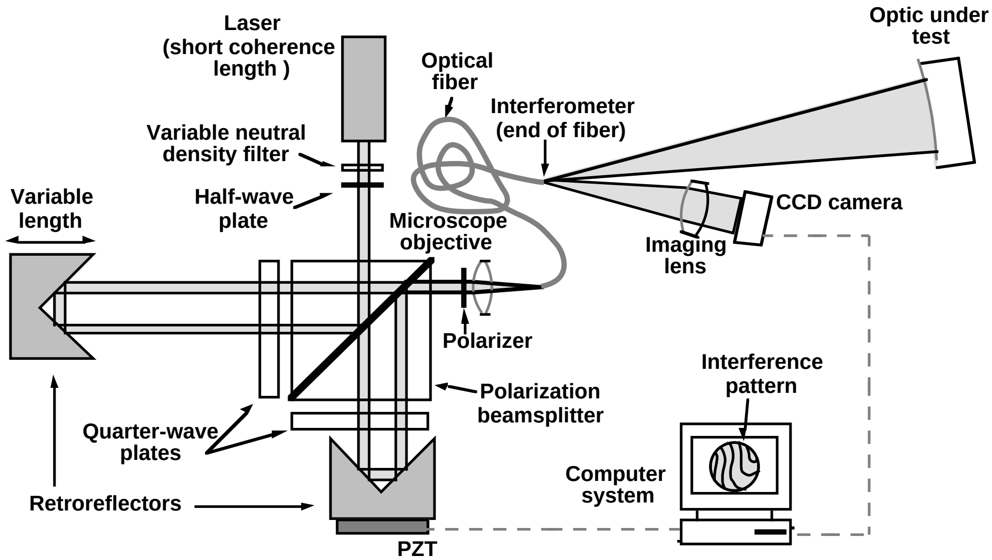
Figure 3b shows the interferometer for testing optics where the ends of two fibers are placed at spatially separated conjugates. Here the two beams are launched into separate equal length fibers and the beam delay is equal to the path length between the fiber ends. Interference on the CCD camera takes place between the phase shifted wavefront from the first fiber that is transmitted through the optic under test and the delayed wavefront from the second fiber. In both configurations the optic under test is imaged onto the CCD camera.

Note that in each configuration the quality of the wavefronts before they are launched into the fibers is not important because the fibers act as spatial filters. Equally important is the fact that the measurement and reference wavefronts encounter no other optical components that can degrade accuracy before they interfere, except the end of the fiber which must be flat over a small area around the core.

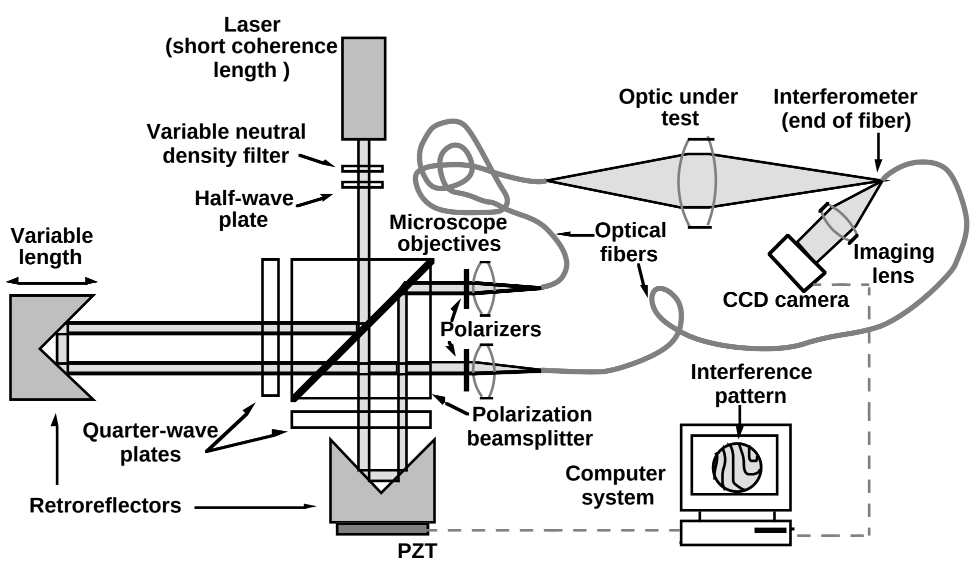
Testing: Several self-consistency tests can be run to determine the quality of the wavefronts from the fibers. One consists of launching two beams into the same fiber with equal path lengths and letting the two diffracted wavefronts interfere directly on the CCD camera. This tests how well the wavefronts are matched. Theoretically the optical path difference should be zero over the full field. Actual measurements show the wavefronts are matched to better than $\lambda/8000$ rms. This test, however, does not indicate how spherical the wavefronts are.

This was done with a second test where the interference between the wavefronts from two different fibers was measured for different angular shears. If the wavefronts are truly spherical the optical path difference should be the same over the full field, independent of angular shear. After subtracting the theoretical two point interference pattern from actual measurements, the wavefront difference was less than $\lambda/1700$ rms. The measurement accuracy appeared to limited not by the quality of the wavefronts but by the unavoidable high density interference pattern in conjunction with nonlinearities in the CCD camera and piezoelectric transducer.

Measurements of EUV optics will be discussed.



(a)



(b)

Figure 3. Two configurations of the phase shifting diffraction interferometer for measuring optics at: (a) a common conjugate; (b) distinct conjugates.

References:

1. Parts of this paper were presented at the OSA Annual Meeting, Portland, OR (1995).